

Generalized degeneracies and their resolution in neutrino oscillation experiments

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Abstract. We discuss a comprehensive way to study the parameter degeneracies in the form of a generalized degeneracy in the neutrino oscillation experiments. First we describe the various degeneracies by considering only neutrino run of the long baseline experiment (LBL), NO ν A. Then we discuss the role of antineutrinos. Later, we present the combined role of T2K (LBL experiment) and ICAL@INO (atmospheric experiment) to resolve these degeneracies. We also discuss the affect of new physics like non-standards interactions (NSI) on the determination of neutrino mass hierarchy in DUNE.

Keywords: Neutrino oscillations, neutrino masses and mixing

1 Introduction

Standard three-flavor neutrino oscillation paradigm consists of six oscillation parameters, these are ; (i) 3-mixing angles ($\theta_{ij}, j > i = 1, 2, 3$) , (ii) 2-mass squared differences ($\Delta m_{i1}^2, i = 2, 3$) and (iii) the Dirac CP phase δ_{CP} . Almost two decades of neutrino oscillation experiments have measured or given hints about these parameters. Currently, the major three unknowns in neutrino oscillation physics are, (i) neutrino mass hierarchy, i.e. the sign of $|\Delta m_{31}^2|$ ($\Delta m_{31}^2 > 0$ is known as the normal hierarchy (NH) or $\Delta m_{31}^2 < 0$ is known as the inverted hierarchy (IH)), (ii) the octant of θ_{23} ($\theta_{23} < \pi/4$ is known as the lower octant (LO) or $\theta_{23} > \pi/4$ is known as the higher octant (HO)) and (iii) the CP phase δ_{CP} , recently T2K results hint towards the maximal δ_{CP} value [1]. The (LBL) oscillation experiments like, T2K [2] and NO ν A [3] which are currently taking data, can provide information on these unknowns. The major obstacles which these LBL experiments have to overcome are the issues of parameter degeneracies i.e. at least two different sets of parameters giving rise to the same oscillation probability.

In this work, we show in a comprehensive way the parameter degeneracies in the test ($\theta_{23} \times \delta_{CP}$)-plane for a given set of representative true values for both the hierarchies. Depending on right (R) or wrong (W) values of (hierarchy-octant- δ_{CP}), there can be 8-possible solutions. We show all the possible observed degeneracies, by considering NO ν A neutrino runs and then we discuss the role of antineutrinos ($\bar{\nu}$ s) to resolve these degeneracies. We then demonstrate how the addition of T2K and ICAL@INO can help in further constraining the degenerate solutions. Sub-leading effects originating from

new physics beyond Standard Model may affect the determination of various unknowns in neutrino oscillation physics. In the near future, this can be probed in the neutrino oscillation experiments. In this respect, we also present a possible new physics scenario, namely NSI and discuss its effect on the determination of neutrino mass hierarchy. The oscillation probabilities which are relevant in our study are considered from [4]. The simulation details and experimental specifications that we considered are given in Ref. [5,6] and the references there in. The current best fit values and 3σ ranges, that we considered in our study are consistent with [7,8].

2 Results

In this section, we present the degeneracies present in both probability and χ^2 level and the role of the $\bar{\nu}$ s to resolve these degeneracies. We also discuss the role of T2K and ICAL@INO. The first column of fig.(1) describes the degeneracies in the appearance channel. The descriptions of the various bands are given in the figure. We see here that the overlapping regions between navy-blue and green bands show the degeneracy for the same values of δ_{CP} . Whereas, by drawing a horizontal line for a given probability one can identify various other degeneracies present at the probability level. Second column shows the degeneracies at the

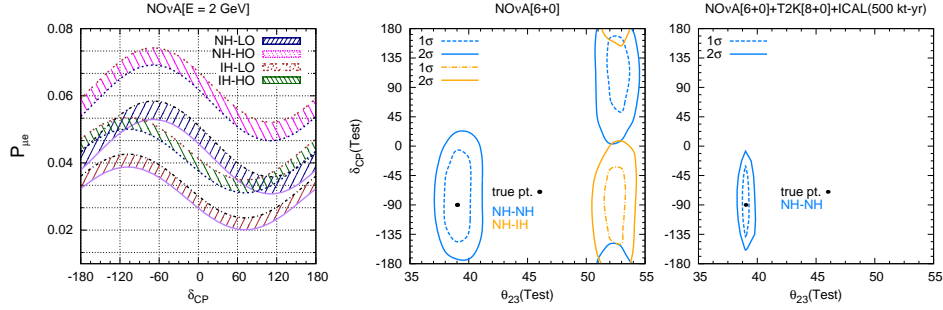


Fig. 1. Here, first (second) column shows the degeneracies in probability (event) level. Whereas third column shows the removal of degeneracies and the precision of the parameters due to the addition of $(\nu + \bar{\nu})$ run from T2K and ICAL@INO.

χ^2 level. In this figure, the true point ($39^\circ, -90^\circ$) is marked with the black dot and the contours around it show the true solutions. Whereas, contours around $\theta_{23} \sim 52^\circ$ show the degeneracies with wrong octant. In the third column we show the allowed region using NO ν A+T2K+ICAL@INO. In this case the degenerate solutions are removed by $\bar{\nu}$ -run and the allowed area is further constrained by T2K+ICAL@INO. The detailed analysis for other sets of parameter values are presented in Ref[5].

In the fig.(2), we describe the role of NSI on the determination of hierarchy for DUNE. We focus on the effects of propagation NSI for which an extra contribution to the Lagrangian can come from dimension-six four-fermion operators

$$: \quad -\mathcal{L}_{\text{NSI}}^{NC} = 2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fC}(\bar{\nu}_\alpha\gamma^\rho P_L\nu_\beta)(\bar{f}\gamma_\rho P_C f) + \text{H.c.} \quad (1)$$

where $\epsilon_{\alpha\beta}^{fC}$ are NSI parameters $\alpha, \beta = e, \mu, \tau$, $f = u, d, e$, C denotes the chirality and G_F is the Fermi constant. In Ref[6], we discussed the role of the diagonal NSI parameter ϵ_{ee} . In the first column of fig. 2, we present the $P_{\mu e}$ vs ϵ_{ee} (model-

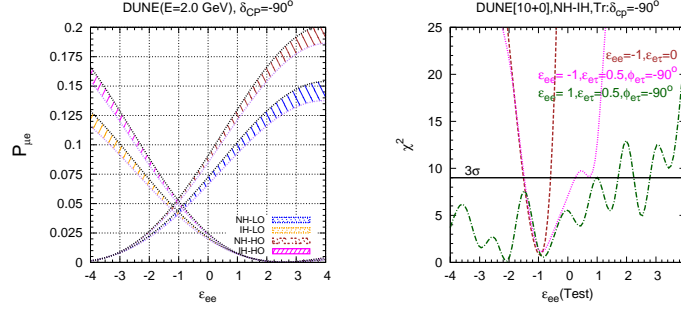


Fig. 2. Here, first column shows the appearance channel probability in presence of NSI parameter, ϵ_{ee} for DUNE. Whereas second column shows the hierarchy sensitivity in presence of NSI parameters ϵ_{ee} , $\epsilon_{e\tau}$.

independent range) for fixed energy, δ_{CP} . The width of the bands are over octant for a given hierarchy as described in the figure. We mainly focus on a special point, $\epsilon_{ee} = -1$ for which, the NSI effect gets nullified by the usual matter term. Hence, in absence of off-diagonal NSI parameters any LBL experiments will not be able to lift this degeneracy. In the second column, we discuss this degeneracy at the χ^2 level and also describe the role of off-diagonal NSI parameter $\epsilon_{e\tau}$. Here, brown curve shows the degeneracy for $\epsilon_{ee} = -1$ at χ^2 level and the pink curve shows that addition of $\epsilon_{e\tau}$ is not able to lift the degeneracy once $\epsilon_{ee} = -1$. Whereas, the green curve shows that if $\epsilon_{ee} \neq -1$ then DUNE can have hierarchy sensitivity if certain ranges of ϵ_{ee} are not allowed.

In conclusion, we describe the (hierarchy–octant– δ_{CP}) generalized degeneracy and their resolution using neutrino oscillation experiments. We also discuss the impact of NSI on the mass hierarchy determination in case of DUNE.

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